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Impurity-related photoionization cross section in a pyramid-shaped quantum dot: Intense laser field and hydrostatic pressure effects

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HIGHLIGHTS

- Laser field effect on the binding energy in a pyramid-shaped nanodot is studied.
- Photoionization cross-section strongly depends on the impurity position.
- For large laser intensities the resonant peak position is red-shifted.
- Hydrostatic pressure blue-shifts the resonant peak and increases its magnitude.

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ABSTRACT

Within the effective mass approximation the binding energy and photoionization cross section of a donor impurity in a pyramid shaped quantum dot under simultaneous action of the hydrostatic pressure and high-frequency laser field have been investigated. We found that: (i) the variation of the binding energy reflects the spatial distribution of the impurity wave function, which is significantly modified by the laser radiation; (ii) the photoionization cross section and resonant peak magnitude depend on the donor position, laser field intensity and pressure. The localization of resonant peak maxima in the doping planes and their dependence on external perturbations are systematically investigated.

1. Introduction

The study of quantum dot structures has received considerable attention in recent years. It opens a new field in both fundamental physics and chemistry, and offers a wide range of potential applications for optoelectronic devices [1]. In this context, the fabrication of high quality artificial heterostructures of different geometries and the investigation of confined carriers in these systems have attracted the interest of many research groups. In particular, quantum dots (QDs) of different shapes have been intensively studied since these systems enable us to confine and control motion of charge carriers in three dimensions by changing the type of geometric confinement. Moreover, the electronic and optical properties of quantum dots can be tuned over a broad range by controlling some internal and external factors such as composition of semiconductors [2], presence and position of the impurity [3–5], shape of the QD [6], hydrostatic pressure [7], effect of static electric or magnetic field [8–10] or high frequency laser field as a time dependent potential [11].

The high hydrostatic pressure is a powerful tool to investigate and control the electronic- related optical properties of semiconductor materials. The main effects of the pressure on the III–V semiconductors are the increasing of band gap and electron effective mass in the Γ-valley of the Brillouin zone, and the reducing of the static dielectric constant [12–15]. There are also some research papers related to the effects of the hydrostatic pressure on the impurity states and optical properties of quantum confined structures [16–19]. The binding energy and photoionization cross section in cylindrical quantum dots (QDs) under hydrostatic pressure and applied electric and magnetic fields are theoretically studied in Ref. [16]. Mora-Ramos et al. [17] have investigated the effect of hydrostatic pressure on exciton properties in cylindrical GaAs quantum dots. Recent reports on the electronic and optical properties of InAs spherical QDs [18] and vertically coupled InAs/GaAs QDs [19] under hydrostatic pressure and electric-field action show a strong dependence on the structural dimensions and external perturbations.

On the other hand, the development of high-power tunable laser sources, such as CO_2 and free electron lasers, has arisen in the discovery of interesting physical phenomena related to the interaction of intense laser fields (ILFs) with carriers in semiconductor

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nanostructures [20–24]. One of the most important consequences of the laser beam action is a considerable change in the electrical and optical properties of low-dimensional systems [25–30], providing the possibility of tailoring the energy spectrum to produce desirable optical transitions. It has been reported that ILF creates an additional geometric confinement of the electronic and impurity states in a cylindrical $Ga_xIn_{1-x}N_yAs_{1-y}$/GaAs QD and enhances the nitrogen and indium concentration effects on the electronic states [25]. Laser effects on the oscillator strength for the intraband transitions in CdS/SiO_2 cylindrical quantum dots have been studied by Radu [26].

For hydrogenic impurity in a cubical QD Yesilgul et al. [27] find a significant dependence of the impurity binding energy and photoionization cross-section on the laser intensity. There are also recent reports of Safarpour et al. [28,29] dealing with the laser radiation effect on the optical properties of a spherical quantum dot confined in a cylindrical nanowire. The eigenfunctions of the structure were obtained within the finite difference approximation and used to calculate the optical absorption coefficient and refractive index changes in a GaAs QD [28], as well as the dependence of the binding energy on the aluminum concentration [29]. Combined effects of the impurity position and electric applied field on the energy levels and donor polarizability in laser-dressed CdS/SiO_2 spherical nanodots were investigated by Niculescu et al. [30] by using a finite element method within a nonperturbative theory that “dresses” both the Coulomb potential and the quantum confinement potential.

As a special type of nanostructure geometry, the pyramid-shaped quantum dots have received increasing attention due to their emergent applications in different areas of modern science and technology (lasers, photonic structures, light detectors and solar cells; see, for example, Refs. [31–33]). Their theoretical treatment within the traditional quantum mechanics approach is mathematically difficult and, in fact, the system can be studied only by numerical techniques [34]. However, the search of analytical solutions of the problem, even solutions with somewhat restricted applicability, could be considered as an important and interesting study. Some recent publications [35,36] have introduced the mirror-reflection boundary conditions for the description of the electronic states in quantum nanostructures with triangular and hexagonal symmetries. This approach is based on some experimental evidences [37] which show that the interaction between the particle and dot boundary frequently is a reflection, giving a clear pattern of standing de-Broglie waves formed by interference of incident and reflected ones.

In this paper we focus on the properties of the shallow donor in a pyramid-shaped quantum dot under the combined effects of the intense laser field and hydrostatic pressure. We use the analytical solutions of the Schrodinger equation proposed by Vorobiev et al. [36] for calculating the binding energy and photoionization cross section dependence on the impurity position and external perturbations.

The paper is organized as follows. In Section 2, we briefly describe the theoretical model. In Section 3 we present results for the electronic structure of the shallow donors in the quantum dot with emphasis on the laser field and pressure effects. Subsequently, the photoionization cross section and resonance peak dependence on the dopant positions in the presence of an intense laser radiation are theoretically investigated. Our conclusions are presented in Section 4.

2. Theory

We consider an InAs pyramid-shaped QD with a square base $a \times a$ and a height $h = a/2$ (Fig. 1) under simultaneous action of the hydrostatic pressure and high-frequency laser field. Within the

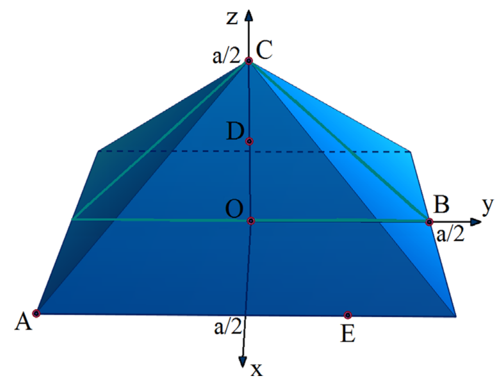

Fig. 1. Pyramidal quantum dot with a square base; the green lines mark the central cross-section. Particular impurity positions $\vec{\mathbf{r}}_i = (0,0,0)$, $(a/2, -a/2, 0)$, $(0, a/2, 0)$, $(0,0,h)$, $(0,0,h/2)$ and $(a/2, a/4, 0)$ are labeled as O, A, B, C, D and E, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

“mirror walls” approach, the confining potential energy inside the dot is zero and the interaction of the particle with the walls has the character of a mirror-like reflection [35]. The even mirror boundary conditions lead to a quasi-periodic structure formed by the initial well and its multiple reflections (see Fig. 1 of Ref. [35]), so that the electron wavefunction (WF) in an arbitrary point inside the dot becomes equivalent with its images in the pyramid's mirror-walls.

Then, within the framework of effective-mass approximation the hydrogenic donor impurity confined by the pyramid-shaped QD can be modeled by the following Hamiltonian:

$$H = -\frac{\hbar^2}{2m^*(P)}\nabla^2 + U(\vec{\mathbf{r}}, \vec{\mathbf{r}}_i, P). \tag{1}$$

The first term is the Hermitian kinetic energy operator for a pressure-dependent effective mass [18]

$$m^*(P) = \left[1 + \frac{15020}{E_g(P)} + \frac{7510}{E_g(P)+341}\right]^{-1} m_0 \tag{2}$$

where $E_g(P)$ is the bulk InAs band gap given by

$$E_g(P,T) = \left(533 + 7.7P - \frac{0.276\,T^2}{T+83}\right) \quad (\text{meV}) \tag{3}$$

calculated for $T = 4$ K.

In Eq. (2) P is the hydrostatic pressure (in kbar) and m_0 is the free electron mass. The pressure-dependent characteristic size (the base side and the height of the pyramidal dot) is obtained from the fractional change in the sample volume [38]

$$a(P) = a(0)\,(1 - S_{11} + 2S_{12})P \tag{4}$$

where $S_{11}(=1.946 \times 10^{-3}\ \text{kbar}^{-1})$ and $S_{12}(=-6.855 \times 10^{-4}\ \text{kbar}^{-1})$ are the elastic constants of the InAs and $a(0)$ is the zero-pressure size.

The last term of Eq. (1) represents the laser-dressed Coulomb interaction between the electron and the shallow donor impurity located at $\vec{\mathbf{r}}_i = (x_i, y_i, z_i)$. In order to consider the effect of the nonresonant intense laser field represented by a monochromatic plane wave linearly polarized along z-axis, we use the Ehlotzky approximation [39]. In the high-frequency limit, the electron “sees” a laser-dressed Coulomb potential.

$$U(\vec{\mathbf{r}}, \vec{\mathbf{r}}_i, P) = -\frac{e^2}{8\pi\varepsilon_0\varepsilon(P)}\left[\frac{1}{\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i+\alpha_0)^2}} + \frac{1}{\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i-\alpha_0)^2}}\right] \tag{5}$$